EROSION PROCESSES AND LANDFORM EVOLUTION ON AGRICULTURAL LAND – NEW PERSPECTIVES FROM CAESIUM-137 MEASUREMENTS AND TOPOGRAPHIC-BASED EROSION MODELLING

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Received 29 February 1996; Revised 20 August 1996; Accepted 25 September 1996

ABSTRACT

Despite growing interest in soil erosion on agricultural land, relatively little attention has been paid to the influence of erosion processes on the pattern of contemporary landform evolution. This in part reflects the problems associated with up-scaling the results of short-term process studies to temporal and spatial scales relevant to the study of landform evolution. This paper presents a new approach to examining the influence of erosion processes on landform evolution on agricultural land which employs: caesium-137 (^{137}Cs) measurements to provide medium-term (*c.* 40 years) estimates of rates of landform change; experimental data and a topographic-based model to simulate soil redistribution by tillage; a mass-balance model of ^{137}Cs redistribution to separate the water erosion and tillage components of the ^{137}Cs 'signatures'; and field observations of water erosion for validation. This approach is used to examine the relative importance of water erosion and tillage processes for contemporary landform evolution at contrasting sites near Leuven, in Belgium, and near Yanan, in Shaanxi Province, China. This application of the approach provides good agreement between the derived water erosion rates and field observations, and hitherto unobtainable insights into medium-term patterns and rates of contemporary landform evolution. At Huldenberg in Belgium, despite rill incision of slope concavities and ephemeral gully incision of the valley floor, contemporary landform evolution is dominated by infilling of slope and valley concavities (rates >0·5 mm a^{-1}) and gradual lowering of slope angles as a result of tillage. In contrast, at Ansai (near Yanan) the slope is characterized by increase in slope angle over most of the length, recession of the steepest section at a rate >5 mm a^{-1} and by increasing planform curvature. At this site, contemporary landform evolution is dominated by water erosion. The constraints on the approach are examined, with particular attention being given to limitations on extrapolation of the results and to the sensitivity of the models to parameter variation. © 1997 by John Wiley & Sons, Ltd.

Earth surf. process. landforms, **22,** 799–816 (1997)
No. of figures: 7 No. of tables: 5 No. of refs: 33
KEY WORDS: landform evolution; caesium-137; soil erosion; erosion modelling; water erosion; tillage erosion; China; Loess Plateau; Belgium

LANDFORM AND PROCESS ON AGRICULTURAL LAND

Field, laboratory and modelling studies undertaken over the last two decades have brought about significant progress in the understanding of erosion processes on agricultural land (Kirkby and Morgan, 1980; Boardman *et al.*, 1989; Wicherek, 1993). A number of studies have addressed the relationship between process and landform by examining landform or topographic controls on water erosion processes (Evans and Cook, 1986; Martz and De Jong, 1987; Loughran *et al.*, 1989; Govers, 1991; Martz, 1992; Auzet *et al.*, 1993). Relatively little attention has, however, been given to the converse aspect of the relationship, namely the influence of erosion processes on the pattern of contemporary landform evolution on agricultural land. This reflects the difficulty of up-scaling

* Correspondence to: T. A. Quine
Contract grant sponsor: ODA
Contract grant sponsor: Royal Society
Contract grant sponsor: British Council
Contract grant sponsor: University of Exeter Research Fund.

CCC 0197-9337/97/090799–18 $17.50

the short-term results of process studies with limited spatial extent (in the case of laboratory studies) or with low spatial resolution (in the case of many field observation programmes) to a temporal and spatial scale relevant to the study of landform evolution. Even if this up-scaling had been possible, it is likely that interpretations concerning landform evolution would have been flawed because of the widespread assumption that the major geomorphic processes operating on agricultural land were associated with water erosion (Boardman and Bell, 1992). Recent experimental and field studies have demonstrated the significant geomorphic impact of soil tillage (Lindstrom *et al*., 1990, 1992; Govers *et al*., 1993, 1994; Revel *et al*., 1993; Lobb *et al*., 1995; Quine *et al*., 1994, 1996) and it is, therefore, clear that any assessment of contemporary landform evolution on agricultural land must account for soil redistribution by both water and tillage.

This paper addresses the need to establish the role of erosion processes in contemporary landform evolution on agricultural land, firstly, by presenting a new approach to linking landform and process on agricultural land, and secondly, using this approach to examine the relative importance of water erosion and tillage processes for contemporary landform evolution at two sites. The potential and limitations of the approach are considered.

A NEW APPROACH TO LINKING LANDFORM AND PROCESS ON AGRICULTURAL LAND

On the basis of the preceding discussion it is possible to define the following requirements for linking landform and process on agricultural land:

1. representative longer-term data must be obtained;
2. the integrated impact of all erosion processes must be determined;
3. the contribution of the individual processes (or, at least, of tillage and water erosion) must be identified.

The first two requirements may be met by the caesium-137 (^{137}Cs) technique (Loughran, 1989), if the assumptions of the approach are accepted (Walling and Quine, 1992). The technique has been well documented elsewhere (Walling and Quine, 1991) and the following outline provides only a brief summary of the basic principles involved. The ^{137}Cs now present in the environment (in those areas unaffected by fallout deposition from the Chernobyl accident) was derived from atmospheric testing of atomic weapons during the period from the mid-1950s to the mid-1970s. After deposition on mineral soils, the ^{137}Cs fallout is adsorbed onto the fine fraction of the soil and subsequently redistributed in association with sediment. Measurements of the current distribution of ^{137}Cs in the landscape provide a basis for estimating soil redistribution. The technique, therefore, provides information on soil redistribution representing all processes operating over a time period of *c.* four decades.

If it is accepted that the ^{137}Cs technique can meet the first two requirements, there still remains the problem of separating the contributions of water erosion and tillage to the pattern of net ^{137}Cs redistribution. This requires the development of new approaches to the interpretation of ^{137}Cs data. The authors have examined two possible approaches to this problem. The first, described elsewhere (Govers *et al*., 1993, 1996), exploits the fundamentally different dependency on topography of water and tillage erosion. A topographic-based model of soil redistribution by tillage and water is used to predict patterns of soil redistribution by different combinations of tillage and water erosion. The relative contribution of the two processes to soil redistribution is established by comparison of ^{137}Cs-derived soil redistribution rates with the model predictions. Where data are available to calibrate the water erosion model (Govers *et al*., 1993), the approach offers the opportunity to examine possible future and past patterns of landform change as well as determining the relative contribution of tillage and water erosion to the ^{137}Cs-derived rates of total soil redistribution. However, the approach has two limitations. Firstly, calculation of ^{137}Cs-derived soil redistribution rates prior to establishing the relative contributions of water and tillage introduces some potential for error, because the relationship between ^{137}Cs loss and soil loss differs for water (surface) erosion and tillage erosion (Quine, 1995; Quine *et al*., 1996). Secondly, the dependence of the approach on the quality of the water erosion model may be problematic when no calibration data are available for the water erosion model. The authors have, therefore, examined the potential of a second approach to the interpretation of ^{137}Cs data which addresses these specific limitations. This second approach was employed in the studies outlined in this paper and may be summarized as follows.

1. Soil samples collected from the study field for ^{137}Cs analysis are used to establish the pattern of net ^{137}Cs redistribution.
2. Topographic data are collected from the study field and used to create a digital elevation model (DEM) of the field.
3. A topographic-based model of soil redistribution by tillage is used in conjunction with the DEM to predict the pattern of soil redistribution rates in the study field resulting from tillage.
4. The predicted rates of soil redistribution by tillage are used in a mass-balance model of ^{137}Cs redistribution (Quine, 1995) to simulate the pattern of ^{137}Cs inventories which would occur as a result of tillage alone.
5. The simulated and measured patterns of ^{137}Cs redistribution are compared. Significant deviations in the pattern are attributed to the impact of surface erosion processes (usually assumed to be water erosion).
6. ^{137}Cs redistribution is again simulated using the predicted rates of soil redistribution by tillage and a range of surface erosion rates. For each point, the surface erosion rate required to obtain a perfect fit between the measured and simulated ^{137}Cs inventories is derived (Quine, 1995).
7. The derived pattern of surface erosion rates is then compared with available independent data for patterns and rates of surface erosion, i.e. water erosion and, where relevant, wind erosion.
8. The relative contributions of tillage and water (and/or wind) erosion to landform evolution may be evaluated using the rates derived in stages 3 and 6.
9. The pattern of landform evolution is derived by combining the rates derived in stages 3 and 6.

The topographic-based model referred to in stage 3 is based on experimental data (Lindstrom *et al*., 1990, 1992; Govers *et al*., 1993, 1994; Revel *et al*., 1993; Lobb *et al*., 1995) which indicate that the displacement of the plough layer by a single tillage operation may be represented by:

$$D = aS + b \tag{1}$$

where D is the mean displacement distance of the plough layer in the direction of tillage (m), S is the tangent of the downslope angle (i.e. negative upslope), and a and b are constants. This relationship indicates that tillage may be simulated as a diffusive process (Govers *et al*., 1993, 1994) and soil fluxes may be calculated as follows:

$$Q_{\mathrm{t}} = k_1 S + k_2 \tag{2}$$

$$Q_{\mathrm{to}} = k_3 S \tag{3}$$

where Q_{t} is the soil flux due to a single tillage pass (kg m^{-1}); Q_{to} is the average soil flux due to tillage in opposing (i.e. upslope one year and downslope the following year) directions (kg m^{-1}); and k_1, k_2 and k_3 are constants. In the procedure outlined above (stage 5 onwards), all significant deviation between measured and simulated ^{137}Cs inventories is attributed to the impact of surface erosion processes. This implies that no uncertainty is associated with the prediction of tillage redistribution. Although this is clearly an over-simplification, two factors provide some justification for the approach. Firstly, very high coefficients of explanation ($r^2 = 0{\cdot}64$ to $0{\cdot}81$ (Lindstrom *et al*., 1990, 1992; Govers *et al*., 1994)) are associated with the experimental derivations of Equation 1, indicating that there is relatively little deviation from diffusive behaviour. Secondly, ^{137}Cs redistribution has taken place over a long period of time and, because of the large number of tillage operations involved, it seems reasonable to assume that random variations from the diffusive relationship would be of negligible significance. In particular, the consistency of the experimental data suggest that the predicted *pattern* of soil redistribution by tillage would closely match the true pattern. The significance of variation in the tillage rates can be examined through sensitivity analysis. This is considered, for the case study sites, in the discussion of the limitations of the approach.

Table I. Study site attributes and data collection

	Huldenberg	Ansai
Location	near Leuven, Belgium	near Yanan, Shaanxi Province, China
Soils	Loessic	Loessic
Mean slope angle (%)	9	20
Maximum slope length (m)	220	94
Aspect	SE-facing	N-facing
Landform	Rolling	Liang and Mao (ridge and rounded peak)
Area sampled (ha)	2·3	0·3
DEM resolution – grid node space (m)	2·5	2
^{137}Cs cores (no.)	110	104
Water erosion data	3 year survey	1 year survey

DERIVATION OF TILLAGE, WATER EROSION AND LANDFORM EVOLUTION DATA: HULDENBERG AND ANSAI

In order to illustrate the potential of the new approach and to test the validity of the results, two examples will be presented. The first is for a site near Huldenberg in Belgium and the second for a site near Ansai on the Loess Plateau in China. Relevant attributes of the sites and their associated databases are summarized in Table I. Both sites are considered to be highly susceptible to water erosion. The site at Huldenberg lies in the loess belt of central Belgium in an area where elevated levels of water erosion on agricultural land have been documented for several years (Poesen and Govers, 1990; Govers, 1991). The site at Ansai lies in the rolling hills area of the Loess Plateau where steep unterraced slopes, erodible soils and intense summer rainstorms combine to produce very high water erosion rates.

Data collection

Topographic data for DEM construction were collected at Huldenberg using a total station (incorporating an electronic theodolite and EDM), and at Ansai using a dumpy level. Simulation of tillage redistribution was undertaken for a 38 ‘year’ period (with topographic correction after each tillage event) to equate to the period from the initiation of ^{137}Cs fallout to the time of sampling. Mean annual tillage erosion and aggradation rates were derived for each sampling point using Equation 4:

$$T_r = \left[\frac{BD\,(E_t - E_0)}{t} \right] \tag{4}$$

where T_r is the tillage redistribution rate (kg m^{-2} a^{-1}); BD is the bulk density (kg m^{-3}); E_t is the elevation at time t (m); E_0 is the initial elevation (m); and t is the time elapsed within the simulation (years).

All water erosion data were derived by field measurement of the volumes of rills and ephemeral gullies. At Huldenberg, the field was monitored for visible evidence of water erosion over a period of 4 years. After each period of potentially erosive precipitation, the field was visited and all rills and gullies were surveyed. On the basis of this work it is possible to present a typical distribution of the rilling, gullying and sediment deposition by water for the field (Figure 1a). Furthermore, it is possible to identify the magnitude of the erosion represented by these features. The ephemeral gully in the main thalweg is incised annually, causing erosion of 5 to 10 m^3 of sediment. In the zero-order slope concavities, incision takes place approximately one year in two, with erosion of 1·5 to 3 m^3 of sediment from the western concavity and 1·5 to 5 m^3 from the eastern concavity. However, it is not possible to quantify the amount of sediment redeposited in the depositional zones, nor the amount of soil eroded by splash and inter-rill processes.

In October 1992, at Ansai, measurements were undertaken of the rill network which had developed during the preceding year at the study site. Local residents indicated that much of the rilling had occurred during a heavy storm in August 1992 and that such storms occurred once every 5–10 years. Because there had been no

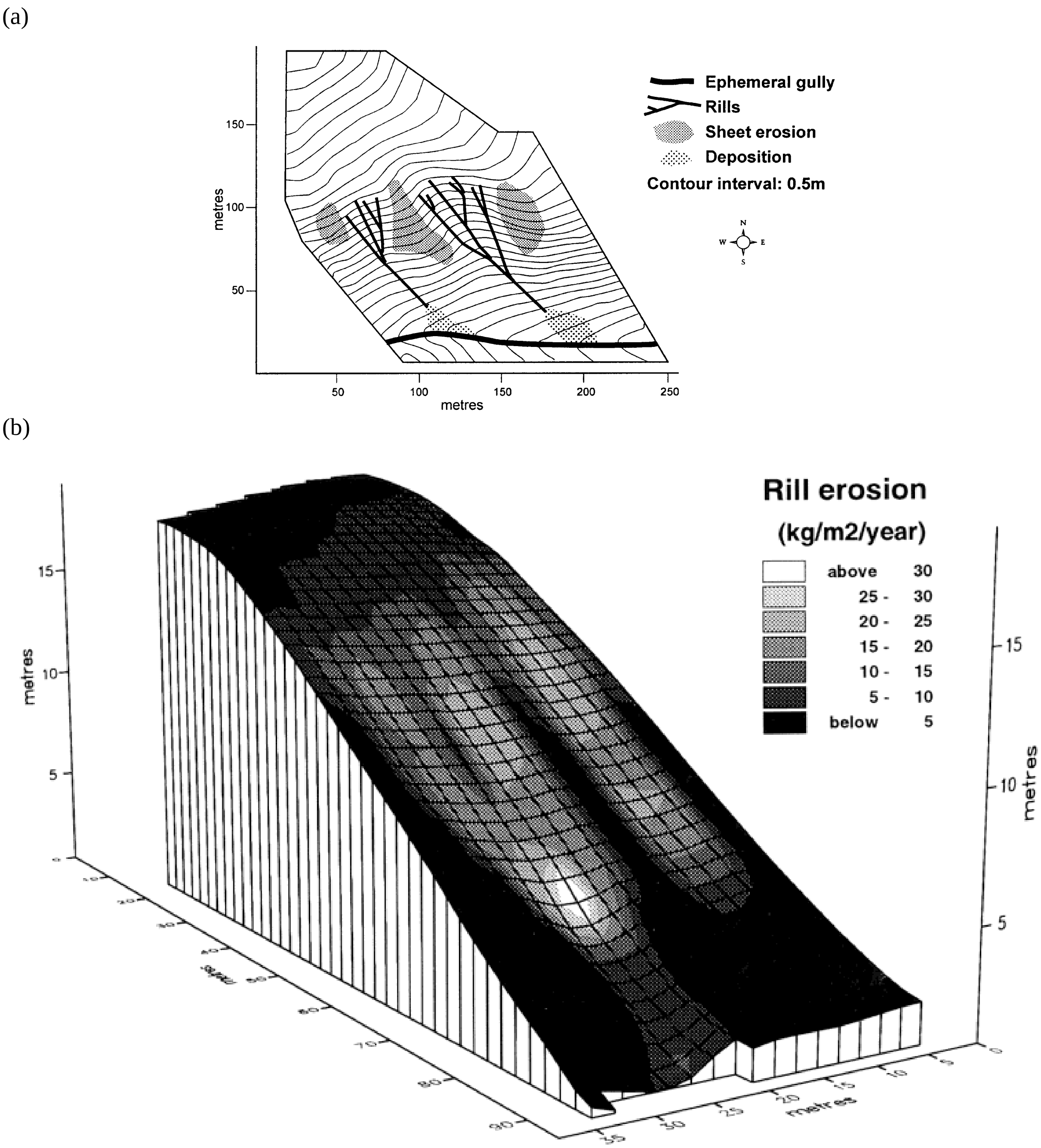
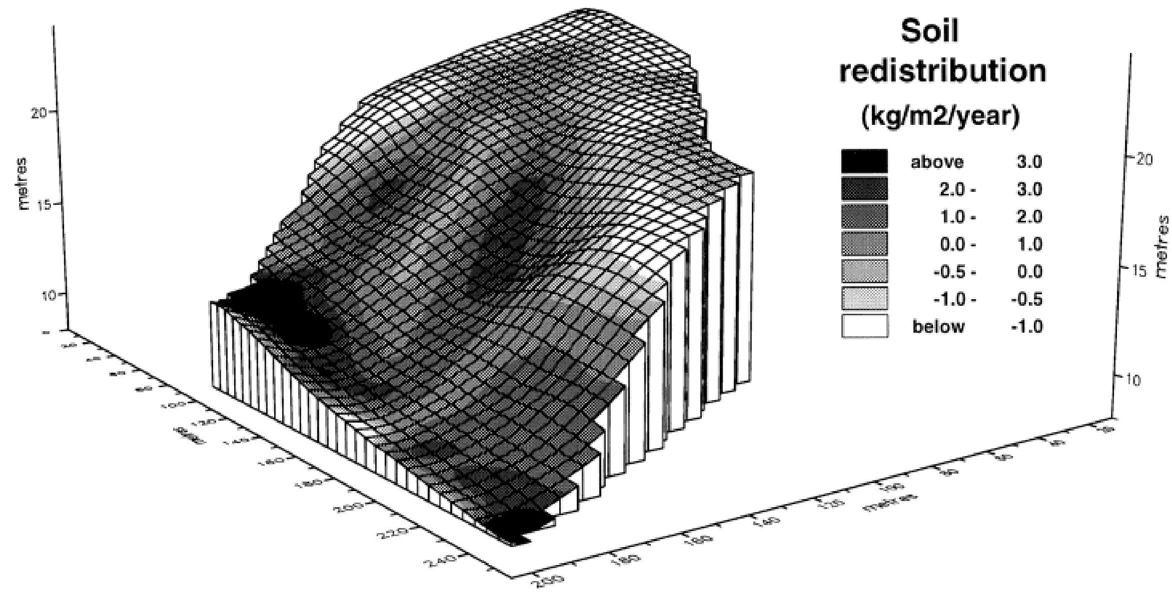


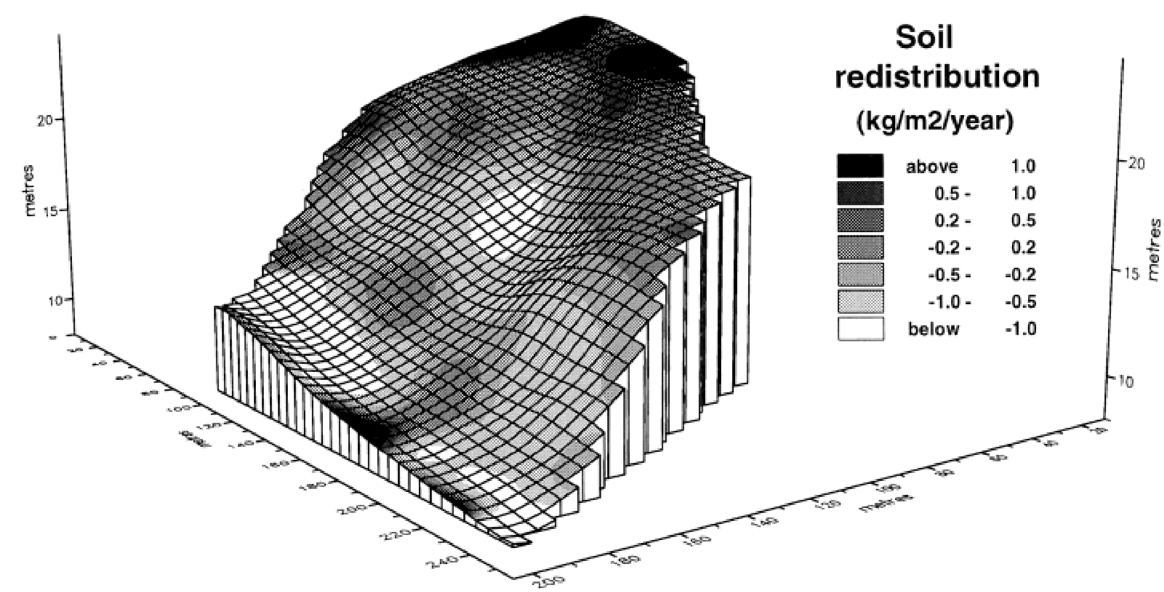
Figure 1. Field evidence for water erosion at the two study sites: (a) the typical distribution of rill and ephemeral gully erosion at Huldenberg over a 4 year period; (b) the spatial distribution of rill erosion rates (resulting from a single year of erosion) at Ansai

disturbance of the site since August and the annual cultivation of the surface was to be undertaken after sampling and measurement were complete, the rates of erosion obtained from the study were taken to represent the annual rate for an 'erosion season' with a *c.* 5 year return period. Rill dimensions were recorded from a point 30 m downslope in the field (upslope of this point there was no visible sign of rilling) to the base of the field. At 2 m intervals in the downslope direction, a tape was extended for 38 m across the slope (a topographically defined zone between planform convexities) and the location, depth and width of each rill (deeper than 1 cm) was recorded. A total of 628 rill cross-sections were measured. The volumetric data were converted to rill

(a)


Soil redistribution (kg/m2/year)
above 3.0
2.0 - 3.0
1.0 - 2.0
0.0 - 1.0
-0.5 - 0.0
-1.0 - -0.5
below -1.0
metres
metres
metres

(b)


Soil redistribution (kg/m2/year)
above 1.0
0.5 - 1.0
0.2 - 0.5
-0.2 - 0.2
-0.5 - -0.2
-1.0 - -0.5
below -1.0
metres
metres
metres

(c)

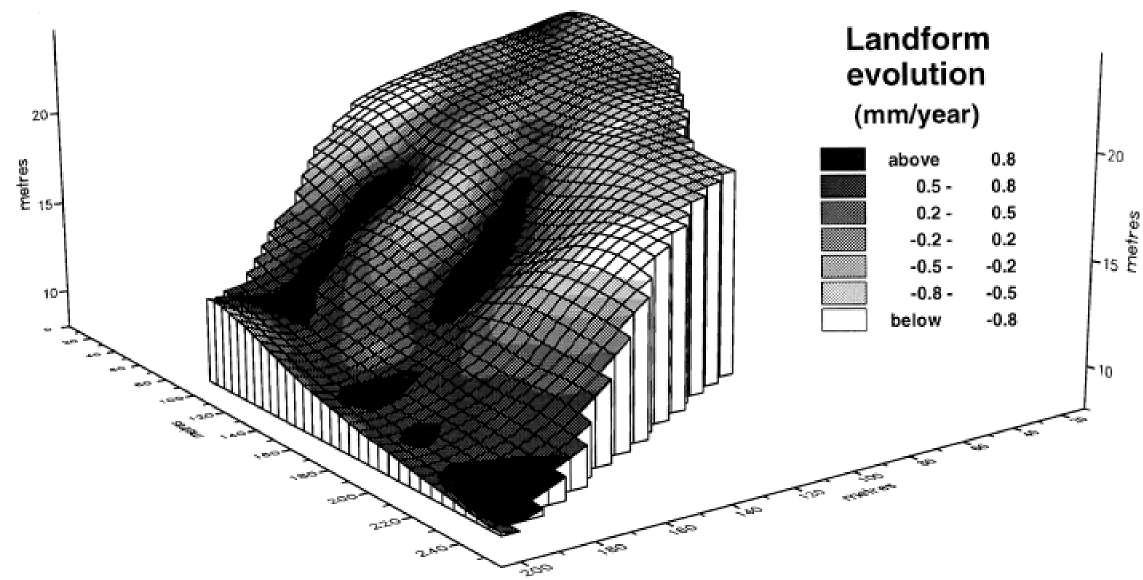


Figure 2. Soil redistribution and landform evolution rates superimposed over isometric projections of the field topography for the site at Huldenberg: (a) tillage rates predicted by the topographic-based model; (b) rates of soil redistribution by water derived from the ^{137}Cs data; (c) rates of landform evolution derived from (a) and (b)

erosion rates for each 1 m segment of each cross-slope transect using Equation 5, and their distribution across the field is shown in Figure 1b.

$$Er_{jk} = \frac{BD}{A_{jk}} \sum_{i=1}^{i=n} (w_i \, d_i \, l) \tag{5}$$

where Er_{jk} is the rill erosion rate for segment j of cross-slope transect k (kg m^{-2} a^{-1}); BD is the bulk density of the eroded material (1350 kg m^{-3}); A_{jk} is the area of segment j of transect k (taken as 1 m^2; n is the number of rills in segment j of cross-slope transect k; w_i is the width of rill i (m); d_i is the depth of rill i (m); and l is the downslope length of the cross-slope transect k (taken as 1 m). It was not possible to estimate rates of splash and inter-rill erosion. There were no visible areas of sediment deposition.

Soil samples were collected for ^{137}Cs analysis, during September 1992 (Huldenberg) and October 1992 (Ansai), using core tubes which were driven into the ground (manually at Ansai and using a petrol-driven percussion corer at Huldenberg) to a depth of 50–60 cm. Sampling to this depth ensured that all ^{137}Cs-labelled soil in the profile was recovered. Where measurements of the ^{137}Cs inventory (activity per unit area) were required, bulk core samples were collected using a 6·9 cm diameter tube; where more detailed information concerning the depth distribution of ^{137}Cs was required, depth incremental samples were collected using a 9·5 cm diameter tube. All samples were air-dried, disaggregated, passed through a 2 mm sieve and weighed. The ^{137}Cs content of the <2 mm fraction of each sample was measured by gamma spectrometry using a hyperpure coaxial germanium detector and multi-channel analyser system. Caesium-137 was detected at 662 keV and counting times, which were typically about 25 000 or 55 000 s, provided results with an analytical precision of approximately ±4 per cent (2 std dev.).

Huldenberg

The DEM and ^{137}Cs data collected from this site were used in the approach outlined in the preceding section to establish the pattern of tillage (Figure 2a) and water erosion (Figure 2b) rates. Tillage was simulated using the topographic-based model discussed above. Because cultivation of the soil is undertaken in opposing directions

Table II. Comparison of measured and ^{137}Cs-derived water erosion rates

	Measured (rill and gully volumes)	^{137}Cs-derived estimate
Huldenberg	3 years	38 years
Thalweg	5–10 $m^3 a^{-1}$	5·1 $m^3 a^{-1}$
Slope concavities	1·5–4 $m^3 a^{-1}$	3·3 $m^3 a^{-1}$
Ansai	1 year	38 years
Sampled area	7·6 $kg m^{-2} a^{-1}$	5·1 $kg m^{-2} a^{-1}$

in alternate years at this site, the soil flux due to tillage was determined using Equation 3. Derivation of an appropriate value of the constant k_3 was based on experimental data for tillage redistribution (Govers *et al*., 1994) obtained from the Huldenberg experimental slope located less than 2 km from the study field. A value of k_3 (Equation 3) of 550 $kg m^{-1} a^{-1}$ was used (two tillage operations per year were simulated, each with a k_3 of 275 $kg m^{-1} a^{-1}$). The influence of this value on the estimation of water erosion from the ^{137}Cs data and on the interpretation of the results is considered in the later discussion of the limitations of the approach.

The pattern of ^{137}Cs-derived water erosion rates (Figure 2b) shows a good agreement with the independent field observations (Figure 1a), both indicating that maximum water erosion occurred in the valley floor thalweg and that high rates were also evident in the zero-order slope concavities. Furthermore, spatial integration of the ^{137}Cs-derived water erosion data permits comparison with the estimates of water erosion rates based on the field observations (Table II). This also shows good agreement between the ^{137}Cs-derived data and the field observations. In view of the lack of agreement between field measurements and ^{137}Cs-derived total erosion rates which has been frequently reported (Quine and Walling, 1993; Quine *et al*., 1996), these are important results because they indicate that when the pattern of soil redistribution represented by ^{137}Cs redistribution, is deconvolved to derive separate estimates of tillage (based on experimental data) and water erosion, the ^{137}Cs-derived water erosion rates show close agreement with independent field observations. The observed agreement also suggests that combination of the predicted tillage redistribution rates and the ^{137}Cs-derived water erosion rates will provide a realistic assessment of contemporary landform evolution. Figure 2c shows the striking pattern which is the result of this combination. Despite field observations of incision of the thalweg and slope concavities by water erosion, contemporary landform evolution in the study area is characterized by infilling of the valley and slope concavities and gradual lowering of the spurs and consequent reduction of slope angles. This pattern is consistent with the dominant role of tillage in landform evolution at the site. This conclusion may be tested further by calculating the percentage contribution of tillage to total soil redistribution (T_p) using Equation 6:

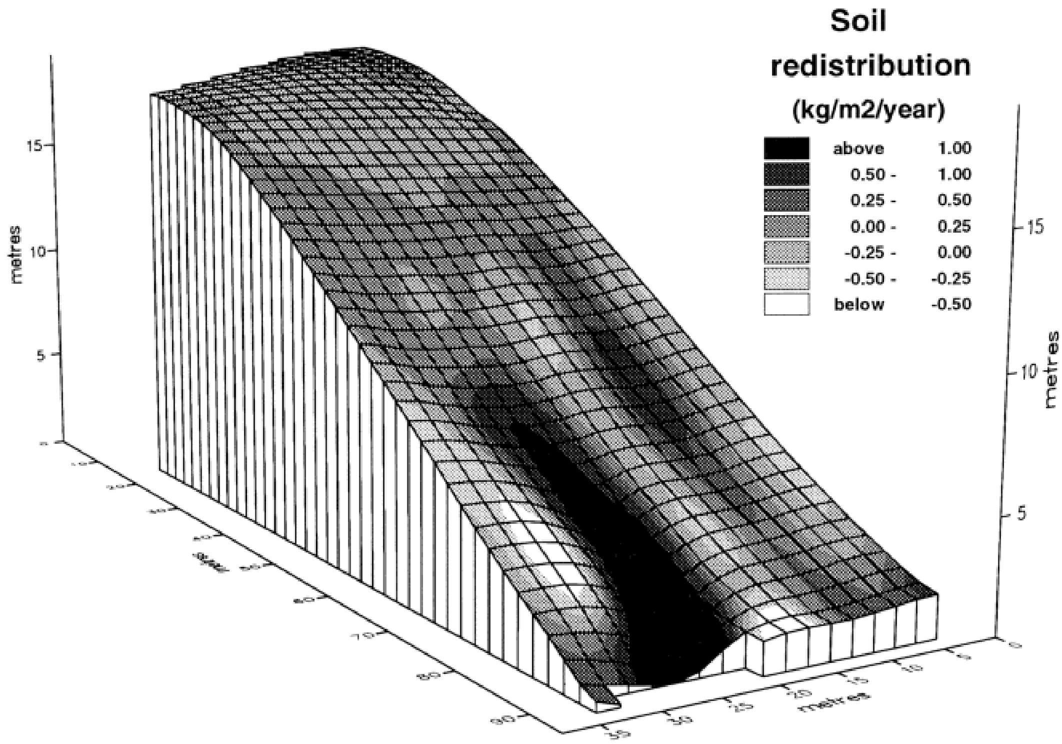
$$T_p = \frac{|T_r| * 100}{|T_r| + |W_r|} \tag{6}$$

where W_r is the ^{137}Cs-derived water redistribution rate. These data for percentage contribution of tillage reinforce the visual evidence of Figure 2c. In over 77 per cent of the study area, T_p exceeds 50 per cent (i.e. the rate of soil redistribution by tillage exceeds the rate of redistribution by water).

Ansai

The procedure outlined above was also applied at the Ansai site to derive tillage (Figure 3a) and water erosion (Figure 3b) rates for the site. Calibration of the topographic model of soil redistribution by tillage was problematic owing to the lack of experimental data relevant to local tillage practices. It is known that the soil is cultivated manually and that the soil is always turned downslope. Because of this unidirectional tillage, the soil flux is best represented by Equation 2. However, there are no published data available to identify appropriate values of k_1 and k_2. Therefore, in the absence of suitable empirical data, a simple semi-deterministic model developed by Quine *et al*. (1993) was used to simulate the downslope tilting of soil blocks produced by this cultivation method. On the basis of this approach, values of k_1 and k_2 (Equation 2) of 15 and 20 $kg m^{-1} a^{-1}$,

(a)


Soil
redistribution
(kg/m2/year)
above 1.00
0.50 - 1.00
0.25 - 0.50
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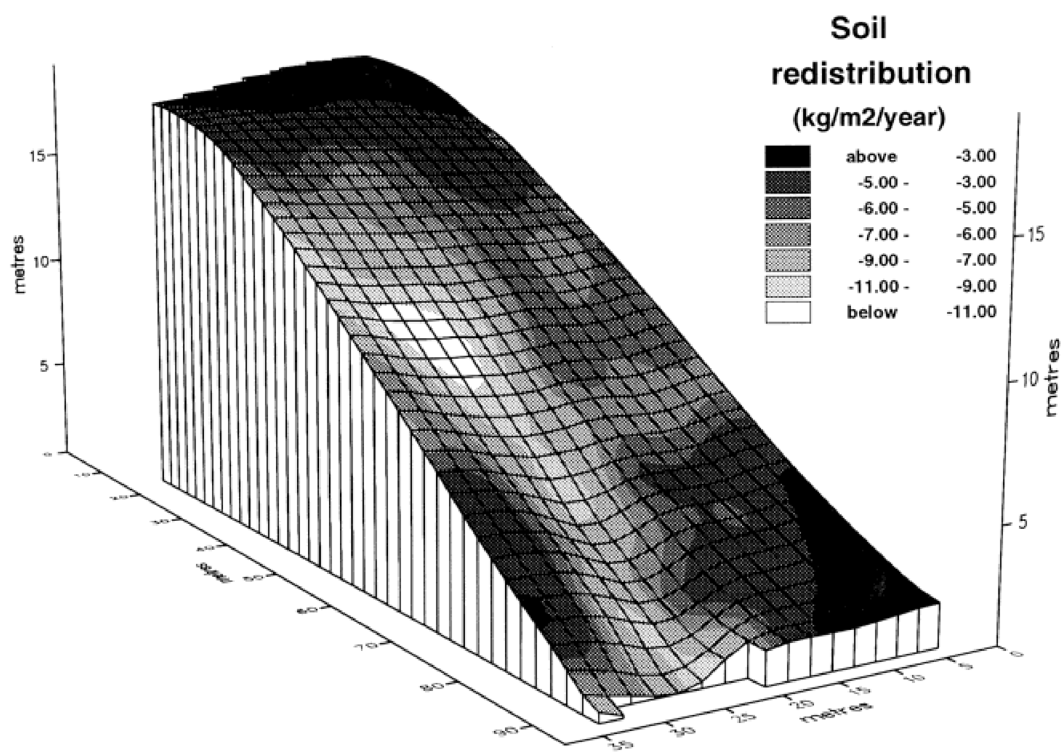
(b)


Soil
redistribution
(kg/m2/year)
above -3.00
-5.00 - -3.00
-6.00 - -5.00
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(c)

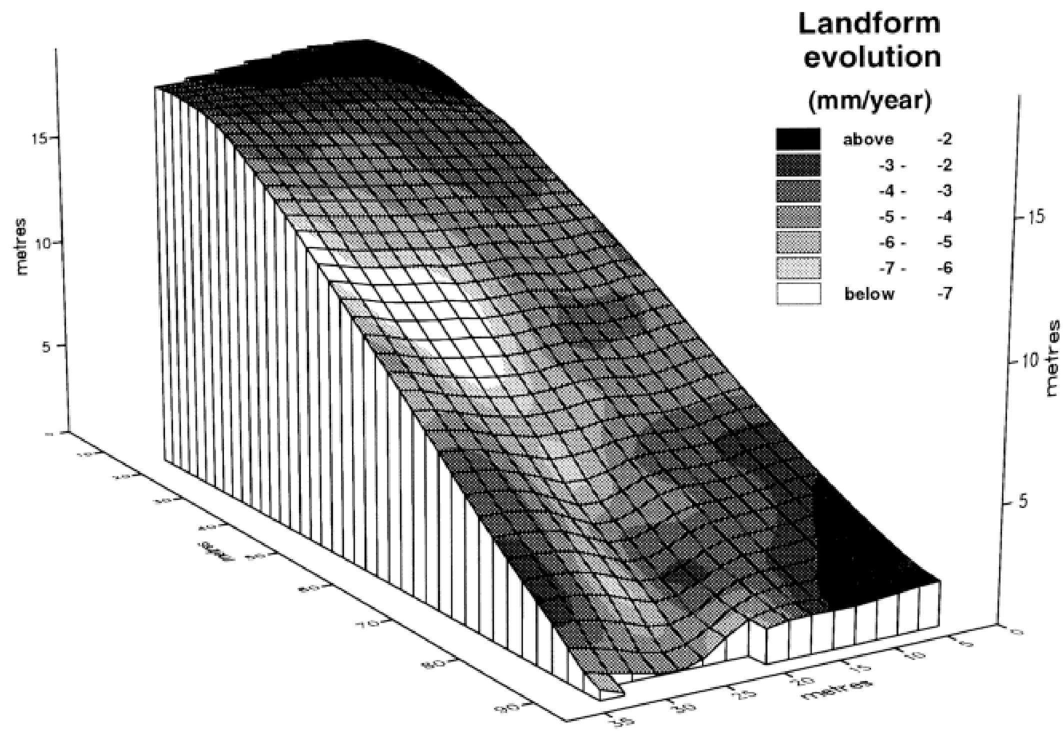


Figure 3. Soil redistribution and landform evolution rates superimposed over isometric projections of the field topography for the site at Ansai: (a) tillage rates predicted by the topographic-based model; (b) rates of soil redistribution by water derived from the ^{137}Cs data; (c) rates of landform evolution derived from (a) and (b)

respectively, were used in the simulation. The relatively low rates of soil redistribution by tillage (Figure 3a) reflect the low energy manual cultivation practice.

Two features are apparent, when the field measurements of rill erosion (Figure 1b) are compared to the pattern of ^{137}Cs-derived water erosion rates (Figure 3b). Firstly, the overall spatial patterns show a strong agreement. Secondly, the magnitude of the peak ^{137}Cs-derived rates are significantly lower than the field measurements. Comparison of the spatially integrated data (Table II) also shows that the measured rate of rill erosion is higher than the ^{137}Cs-derived rate of water erosion. These observations accord with expectations for two reasons. First, the ^{137}Cs-derived water erosion rates would be expected to show lower peak values and a wider distribution than the field measurements because the ^{137}Cs present in the soil has been subject to continuous lateral mixing by tillage, resulting in smoothing of the distribution (Quine *et al*., 1996). Secondly, higher rates were expected for the single-year field observation data because the erosion recorded was the result of an ‘erosion season’ with a *c.* 5 year return period.

The ^{137}Cs-derived rates of water erosion at Ansai are almost an order of magnitude greater than the predicted rates of tillage redistribution. In this context, the small uncertainty surrounding the calibration of the tillage redistribution model would appear to be of relatively little significance (it is considered further in the following section). The predicted tillage and ^{137}Cs-derived water erosion rates have, therefore, been combined to derive an estimate of the pattern of contemporary landform evolution at the site (Figure 3c). Not surprisingly, this indicates that contemporary landform evolution at the site at Ansai is dominated by water erosion (water erosion rates exceed tillage redistribution rates over 99 per cent of the field area). The data suggest that the middle, steepest portion of the slope is receding at an average rate in excess of 5 mm a^{-1} and is characterized by increasing planform curvature. Lower rates of erosion at the crest are leading to a gradual increase in slope angle over most of the slope. At the base of the field, soil accumulation as a result of downslope tillage has almost kept pace with removal by water, leading to the creation of a relatively level area and a step to the next field. These patterns derived from the study results are consistent with observation of the surrounding

Figure 4. The convex upper surface of the Loess Plateau near Ansai, characterized by parallel zones of longitudinal incision leading to increasing planform curvature with increasing slope length

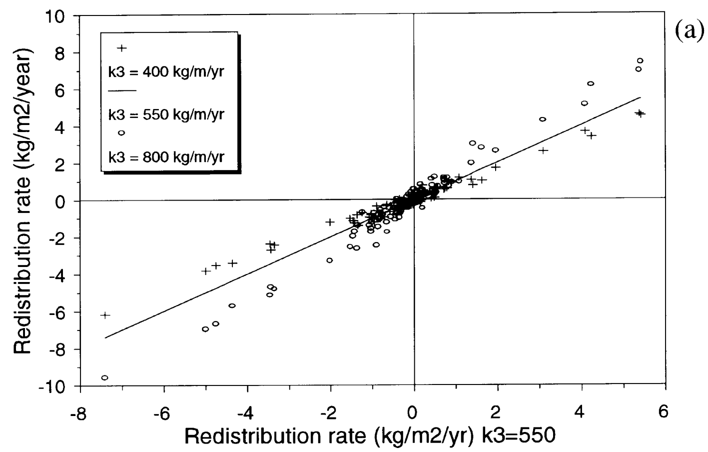
landscape. Figure 4 shows the convex upper surface of the Loess Plateau close to the study field to be characterized by parallel zones of longitudinal incision leading to increasing planform curvature with increasing slope length and a series of steps between the fields. This pattern provides further qualitative confirmation of the results and an indication of the representativeness of the data.

LIMITATIONS AND UNCERTAINTIES

Although the approach outlined and employed at the two study sites offers considerable potential for the investigation of contemporary landform evolution, it is important to recognize the associated limitations and uncertainties. Specific uncertainties and limitations associated with the ^{137}Cs technique have been discussed elsewhere (Walling and Quine, 1991, 1992; Sutherland, 1991; Quine 1995; Owens and Walling, 1996; Quine *et al*., 1996) and attention here focuses only on the approach outlined above. Two aspects will be addressed in detail, namely, the sensitivity of the rate estimates and interpretations to variation in key model parameters, and the limitations on extrapolating the results. Two models are employed in this approach. The first simulates soil redistribution by tillage and the second simulates ^{137}Cs redistribution in association with soil redistribution. Sensitivity of results and interpretations to parameter variation in both is considered.

Sensitivity to model parameters – tillage simulation

As is evident from Equations 1 to 3 and the preceding discussion, the topographic-based model of soil redistribution by tillage has only one calibration parameter (k_3) for the Huldenberg simulation and two (k_1 and k_2) for the Ansai simulation. Furthermore, in the case of the Huldenberg simulation, independent experimental data are available to guide the choice of value for k_3. A reasonable level of confidence is, therefore, associated with the value for k_3 ($550\,kg\,m^{-1}\,a^{-1}$) which was used to represent a mouldboard ploughing operation and subsequent discing and harrowing (experimental estimates of k_3 for a single pass of a mouldboard plough lie in the range $250–350\,kg\,m^{-1}$). Despite this level of confidence, two further simulations were undertaken for the Huldenberg site. On the basis of the experimental data, it is evident that a value for k_3 lower than $400\,kg\,m^{-1}\,a^{-1}$ would be inappropriate where mouldboard ploughing is used in conjunction with other annual tillage practices.



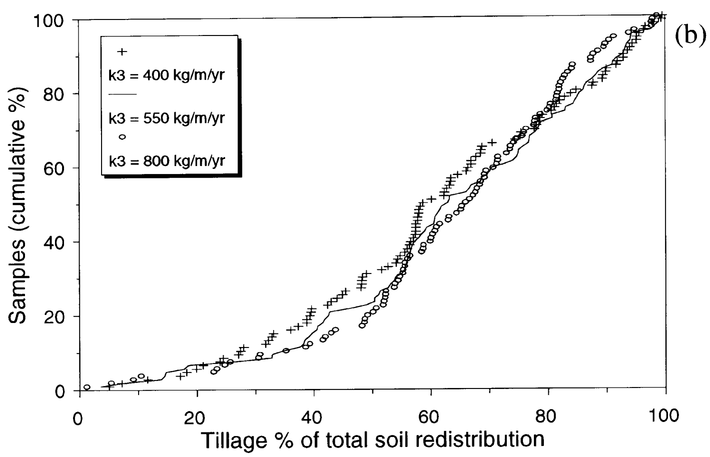


Figure 5. Sensitivity of the predictions at the Huldenberg site to variation in the value of the constant (k_3 (kg m^{-1} a^{-1}) used in the simulation of soil redistribution by tillage: (a) water redistribution rates predicted with values of k_3 of 400 and 800 kg m^{-1} a^{-1} plotted against predicted water redistribution rates with a k_3 of 550 kg m^{-1} a^{-1}; (b) cumulative plot of percentage contribution of tillage to total soil redistribution for the simulations used in (a)

Equally, in situations where ploughing is undertaken more than once in each year, values of k_3 which are significantly higher than the 550 kg m^{-1}a^{-1} used could be expected. The two simulations undertaken, therefore, included a 'low' tillage scenario with a k_3 value of 400 kg m^{-1}a^{-1} and a 'high' tillage scenario with a k_3 value of 800 kg m^{-1}a^{-1}. Figure 5 illustrates the deviation in water erosion estimates obtained in these additional simulations from the results of the simulation using a k_3 value of 550 kg m^{-1}a^{-1} (Figure 5a) and shows cumulative curves for the contribution of tillage to total soil redistribution (Figure 5b) for each of the simulations. The individual point data have been used to construct the cumulative curves in Figure 5b so that no artificial smoothing is introduced by interpolation procedures. It is apparent from Figure 5 and the summary data presented in Table III that at this site the procedure is very robust with regard to variation in the value of k_3, and neither of the additional simulations present results which would change the interpretation that contemporary landform evolution at the Huldenberg site is dominated by soil redistribution by tillage.

There was clearly greater uncertainty regarding parameterization of the tillage model for the Ansai site, and little basis on which to establish a range of values for sensitivity analysis. A second simulation for this site was undertaken with doubled values of k_1 and k_2 (to 30 and 40 kg m^{-1}a^{-1}), and Figure 6a illustrates the deviation in water erosion estimates obtained in this simulation from the initial estimates (obtained with values of k_1 and k_2 of 15 and 20 kg m^{-1}a^{-1}, respectively). Figure 6b shows cumulative curves for the contribution of tillage to total

Table III. Sensitivity of simulations of the Huldenberg site to variations in the parameters used in tillage simulation ('default' simulation in bold).

Value of k_3 ($kg\,m^{-1}\,a^{-1}$)	Value of NL (cm)	Arithmetic mean rate of soil erosion by water for the sample sites ($kg\,m^{-2}\,a^{-1}$)	Percentage of sample sites for which the thresholds of T_p (contribution of tillage to total soil redistribution) apply		
			T_p<25%	T_p>50%	T_p>75%
400	0·5	0·18	9	68	32
550	**0·5**	**0·19**	**7**	**77**	**37**
800	0·5	0·23	7	79	33

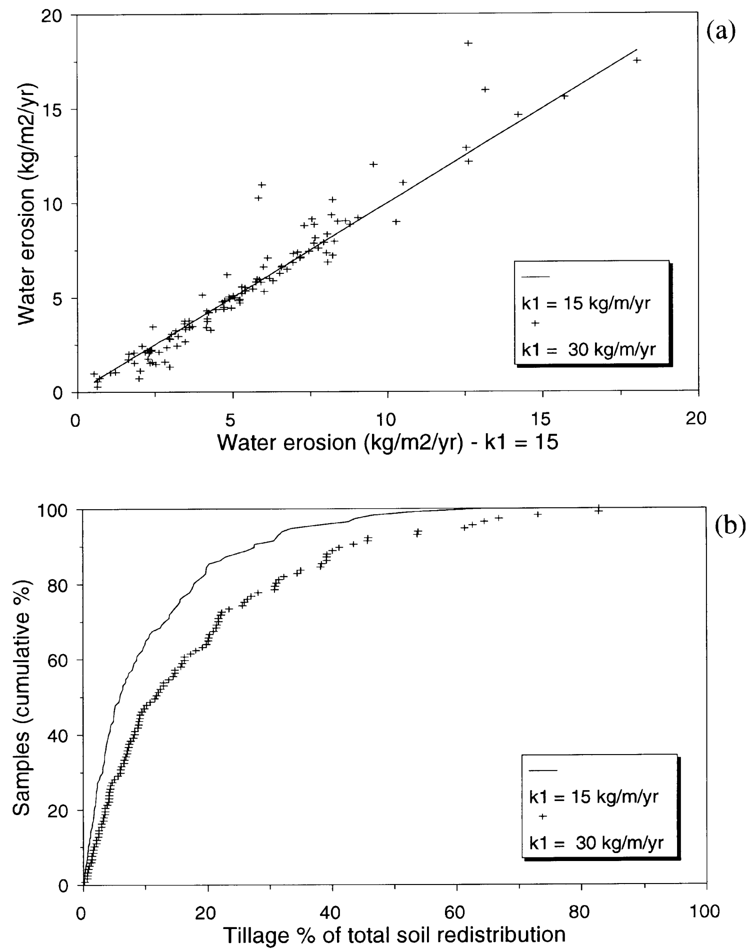


Figure 6. Sensitivity of the predictions at the Ansai site to variation in the value of the constants k_1 and k_2 ($kg\,m^{-1}\,a^{-1}$) used in the simulation of soil redistribution by tillage: (a) water redistribution rates predicted with values of k_1 and k_2 of 30 and 40 $kg\,m^{-1}\,a^{-1}$, respectively, plotted against predicted water redistribution rates with values of k_1 and k_2 of 15 and 20 $kg\,m^{-1}\,a^{-1}$, respectively; (b) cumulative plot of percentage contribution of tillage to total soil redistribution for the simulations used in (a)

soil redistribution for both of the simulations, and Table IV presents summary statistics. Again, it is apparent that the procedure is robust with regard to variation in the values of k_1 and k_2 employed at this site, and the interpretation that contemporary landform evolution at the Ansai site is dominated by water erosion is supported by the second Ansai simulation. A third simulation was conducted for the Ansai site using quadrupled values of k_1 and k_2 (60 and 80 $kg\,m^{-1}\,a^{-1}$); this had little impact on the derived mean water erosion rate (5·89 $kg\,m^{-2}\,a^{-1}$) and the area over which tillage contributed more than 50 per cent of total soil redistribution was increased to only 17 per cent. However, because of the high tillage erosion rates produced by this simulation, it was necessary to invoke some areas of soil deposition by water on steep slope elements in order to

Table IV. Sensitivity of simulations of the Ansai site to variations in the parameters used in tillage simulation ('default' simulation in bold).

Value of k_1 ($kg\,m^{-1}a^{-1}$)	Value of k_2 ($kg\,m^{-1}a^{-1}$)	Arithmetic mean rate of soil erosion by water for the sample sites ($kg\,m^{-2}a^{-1}$)	Percentage of sample sites for which the thresholds of T_p (contribution of tillage to total soil redistribution) apply		
			T_p<25%	T_p>50%	T_p>75%
15	**20**	**5·47**	**88**	**1**	**0**
30	40	5·60	74	7	1

match the predicted ^{137}Cs inventories to the measured values. Such deposition is highly unlikely and was not supported by any field evidence. It may, therefore, be suggested that the quadrupled values of k_1 and k_2 (60 and $80\,kg\,m^{-1}a^{-1}$) exceed the true values and that the latter are more likely to lie in the range represented by the previous simulations (k_1=15–30 $km\,m^{-1}a^{-1}$ and k_2=20–40 $kg\,m^{-1}a^{-1}$).

Sensitivity to model parameters – simulation of ^{137}Cs redistribution

The approach used in the simulation of ^{137}Cs redistribution and the sensitivity of the model to the main parameters is discussed in detail elsewhere (Quine, 1995). The potential for error in this simulation is minimized by use of parameters for which independent data are available. For example, the annual fallout of ^{137}Cs to the ground surface was simulated in this study using data based on published fallout records from Milford Haven (UK) and New York (USA) which are taken to be representative of the pattern of fallout for the northern hemisphere. Although some uncertainty surrounds the use of these data for the Chinese site in particular, earlier analysis (Quine, 1995) demonstrates that, as long as fallout is distributed over several years from the 1950s to the 1970s with a peak in the early 1960s, the simulation has a low sensitivity to the pattern of fallout input and the resultant variations in predicted ^{137}Cs redistribution are small (maximum of ±1·5 per cent at erosion rates of $10\,kg\,m^{-2}a^{-1}$).

Nevertheless, the simulation of ^{137}Cs redistribution is sensitive to two parameters, namely the plough depth and the initial depth distribution of the ^{137}Cs fallout (i.e. immediately after contact with the ground surface). Use of evidence from depth distributions of ^{137}Cs, soil profile observation, and conversations with land-users allows the plough depth to be estimated with a relatively high degree of confidence (estimates used were 0·2 m at Huldenberg and 0·15 m at Ansai). In contrast, few data exist concerning the initial depth distribution of ^{137}Cs after fallout. The approach employed assumes that the initial depth distribution has the following form:

$$C_d = C_f k e^{-kd} \tag{7}$$

$$k = \frac{\ln(10)}{NL} \tag{8}$$

where C_d is the ^{137}Cs activity ($Bq\,m^{-2}\,cm^{-1}$) at depth d (cm); C_f is the ^{137}Cs fallout input ($Bq\,m^{-2}$); k is defined by Equation 8; and NL is the depth above which 90 per cent of fallout input is found (cm).

The simulated surface concentration of ^{137}Cs during the period of ^{137}Cs fallout and, therefore, the amount of ^{137}Cs lost per unit mass of soil eroded by water (or other surface processes) is determined by the value used for parameter NL. As the value of NL is increased, the predicted surface concentration declines and, therefore, a higher water erosion rate is required to obtain the same level of ^{137}Cs depletion. Experimental evidence for an appropriate value of NL for fallout ^{137}Cs is difficult to obtain because of the low concentrations of ^{137}Cs involved and because of the problems associated with obtaining depth incremental soil samples at millimetre precision. However, results of experiments on gleyed brown earths (15 per cent clay; 42 per cent silt; 43 per cent sand) of the Rixdale series in Devon (He, 1993; Owens, 1994) suggest that a value of 0·8 cm for NL may be of the appropriate magnitude. However, for the simulations discussed above, a smaller value (0·5 cm) of NL was used. It is intended that this should account for synchronous fallout deposition and water erosion, which could be expected to depress the value of NL. In the present state of knowledge, this value represents an informed estimate rather than a definitive value. It is, therefore, appropriate to examine the sensitivity of the predictions to

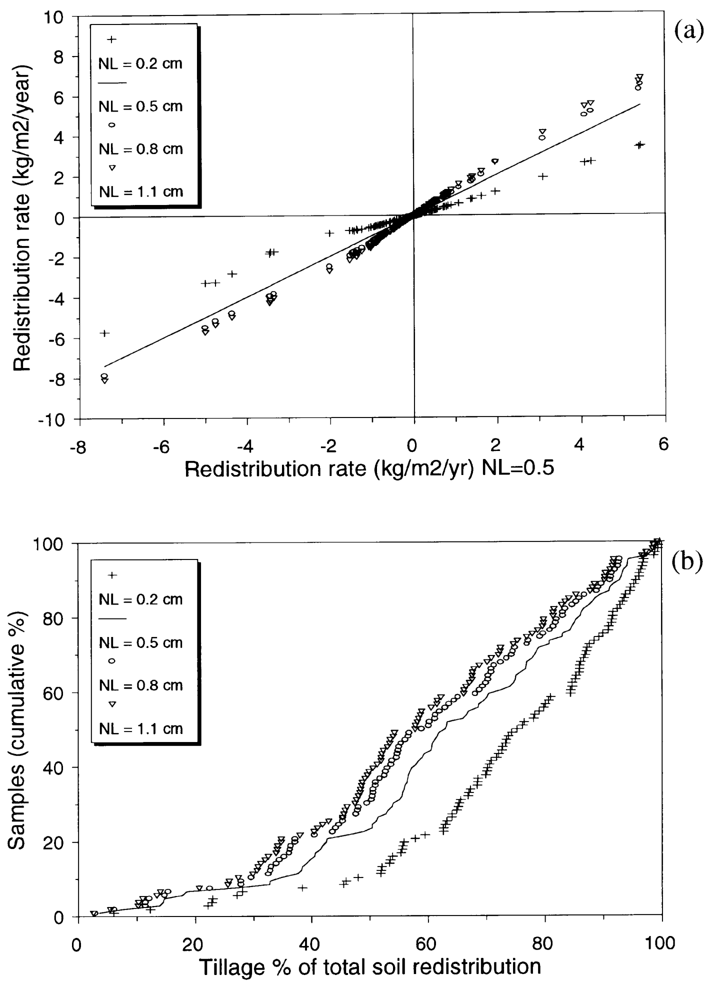


Figure 7. Sensitivity of the predictions at the Huldenberg site to variation in the value of the constant *NL* (cm) used in the simulation of ^{137}Cs redistribution in association with soil redistribution: (a) water redistribution rates predicted with values of *NL* of 0·2, 0·8 and 1·1 cm plotted against predicted water redistribution rates with a value of *NL* of 0·5 cm; (b) cumulative plot of percentage contribution of tillage to total soil redistribution for the simulations used in (a)

variation in the value of *NL*, and this has been undertaken for the Huldenberg site. In the sensitivity analysis, the effect of increasing *NL* was examined through use of the values 0·8 cm (as obtained in the experiments of He (1993) and Owens (1994)) and 1·1 cm, and the effect of reduction of *NL* was examined through use of a value of 0·2 cm. Figure 7 provides a comparison of the water erosion rate estimates obtained with *NL* values of 0·2, 0·8 and 1·1 cm with those obtained with an *NL* value of 0·5 cm (Figure 7a), and shows cumulative curves for the contribution of tillage to total soil redistribution (Figure 7b) for each of the simulations. Table V provides summary data. It is evident that the procedure has a relatively low sensitivity to increase in the value of *NL*, with only a 31 per cent increase in the arithmetic mean water erosion rate when *NL* is increased from 0·5 to 1·1 cm. Reduction of the value of *NL*, below the 0·5 cm used in the simulation, produces larger deviations in the predictions. However, it should be noted that the value of 0·5 cm was already lower than the experimentally derived measure (albeit for a different soil type). In the present state of knowledge regarding initial depth distributions of ^{137}Cs fallout, it is necessary to treat the absolute values of predicted water erosion rates with caution. Nevertheless, it is clear from both Figure 7 and Table V that values of *NL* in the range of 0·5–1·1 cm provide similar results. Most importantly, none of the additional simulations performed in the sensitivity analysis present results which would change the interpretation that contemporary landform evolution at the Huldenberg site is dominated by soil redistribution by tillage.

Table V. Sensitivity of simulations of the Huldenberg site to variations in the parameters used in simulation of ^{137}Cs redistribution ('default' simulation in bold).

Value of k_3 ($kg\,m^{-1}\,a^{-1}$)	Value of *NL* (cm)	Arithmetic mean rate of soil erosion by water for the sample sites ($kg\,m^{-2}\,a^{-1}$)	Percentage of sample sites for which the thresholds of T_p (contribution of tillage to total soil redistribution) apply		
			T_p<25%	T_p>50%	T_p>75%
550	0·2	0·11	5	89	50
550	**0·5**	**0·19**	**7**	**77**	**37**
550	0·8	0·22	8	69	28
550	1·1	0·25	8	61	27

Extrapolation of results

The foregoing discussion has demonstrated that the proposed approach is sufficiently robust to provide valuable insights into *contemporary* landform evolution for the studied sites. However, it is important to recognize the constraints on extrapolation of the results to longer time-scales. By definition, the evidence from ^{137}Cs redistribution only provides direct information concerning landform evolution over the period of time since the initiation of fallout (i.e. since the mid-1950s). The rates are, therefore, time-specific averages for the period in question and they can not be linearly extrapolated into the future for two reasons. Firstly, linear extrapolation is inappropriate because of the landform alteration produced by the processes and the influence this has on the future operation of the processes. Secondly, the rates are not equivalent to the rates at the time of sampling; instead they represent 'long-term' averages over a period of significant agricultural change and, therefore, probable temporal variation in both tillage and water erosion rates. This is particularly true of the Huldenberg site, where tillage erosion rates may be expected to have risen as a result of the increasing power of the tillage machinery used, and changes in agricultural practice have brought about an increased sensitivity to water erosion.

Investigation of longer-term future landform evolution can be best addressed through the use of appropriate 'data-abstemious' models (although these are also constrained by uncertainties regarding future changes in agricultural practice, etc.). In this respect, topographic-based models of sediment transport rate along a hillslope, as pioneered by Kirkby (1971; Kirkby *et al*., 1987), appear to offer the greatest promise (Govers *et al*., 1993, 1996; Desmet and Govers, 1995). Studies using the approach outlined in this paper can clearly contribute to such longer-term simulation by directing parameterization or through use in refinement or validation of water erosion predictions.

LINKING LANDFORM AND PROCESS: CONCLUSIONS

A new approach has been proposed for the assessment of contemporary landform evolution on agricultural land and its interpretation in relation to the dominant geomorphic processes. Validation of the approach has been provided by the results of two case studies. The approach combines four methodologies: (1) a tracer (^{137}Cs in this case) has been used to identify the pattern of landform evolution; (2) experimental data have been used to determine the geomorphic impact of the most predictable process (tillage in this case); (3) models have been used to predict rates for the most predictable process from the experimental data, and to derive rates for the least predictable process (water erosion in this case) from the tracer signal; (4) field observations have been used to validate the derived process patterns and rates for the least predictable process. The combination of these methodologies has yielded insights into contemporary landform evolution and erosion processes that would be unattainable using the individual methodologies in isolation, and it is suggested that this combination of methodologies may have wider application to the challenge of linking landform and process.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the ODA and the Royal Society for the work undertaken in China, and by the British Council and the University of Exeter Research Fund for the work

undertaken in Belgium. The field assistance provided by staff in the Middle Yellow River Bureau is also gratefully acknowledged.

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